



Jet Propulsion Laboratory
California Institute of Technology
National Aeronautics and Space Administration

Atom Interferometry for Fundamental Physics and Gravity Measurements in Space

James M. Kohel
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109



Technology Overview: Cold Atom Sensors

Laser-cooled atoms are used as freefall test masses. The gravitational acceleration on atoms is measured by atom-wave interferometry. The fundamental concept behind atom interferometry is the quantum mechanical particle-wave duality. One can exploit the wave-like nature of atoms to construct an atom interferometer based on matter waves analogous to laser interferometers.



The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"



Steven Chu

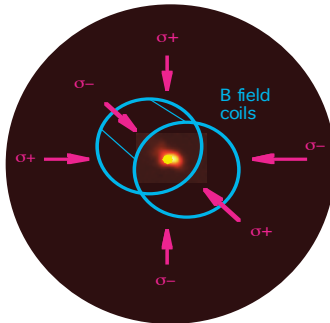


Claude Cohen-Tannoudji



William D. Phillips

Laser Cooling and Atom Interferometry



A cloud of laser trapped and cooled Cs atoms in magneto-optical trap, with cloud fluorescence in false color.

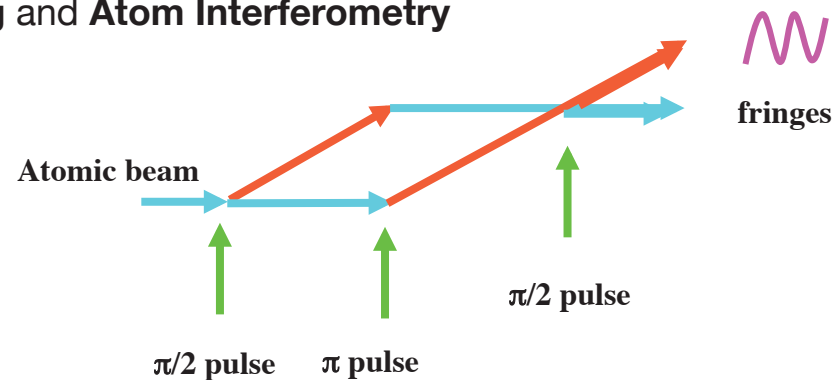


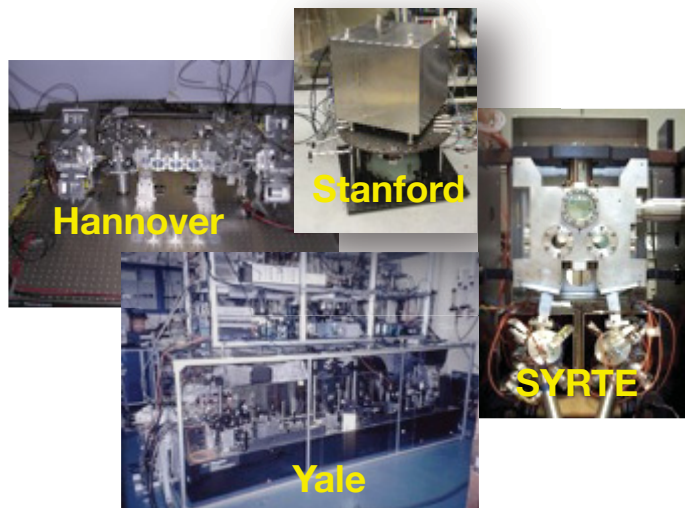
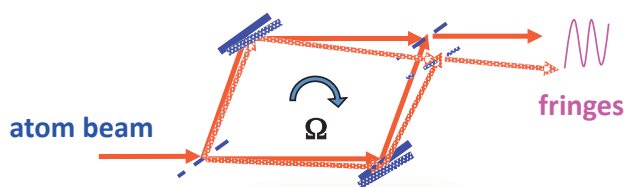
Illustration of Mach-Zehnder atom-wave interferometer which is realized by a sequence of laser pulses.



Inertial Sensing with Atom Interferometers

Rotational sensing

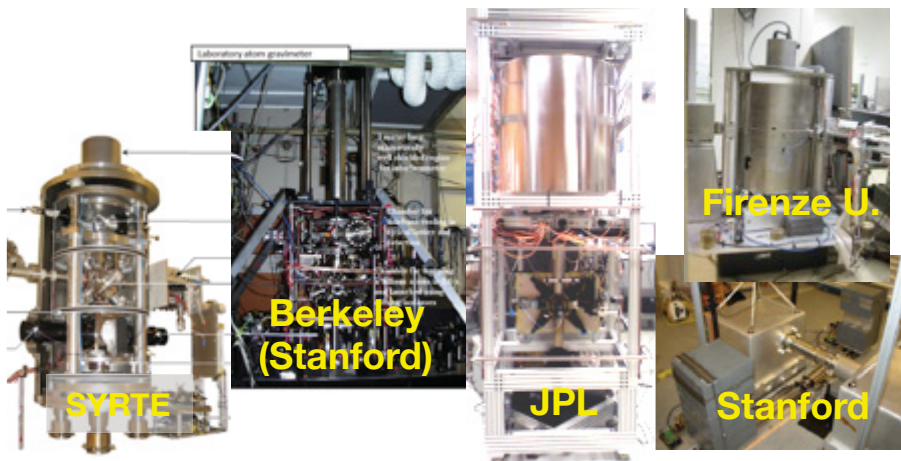
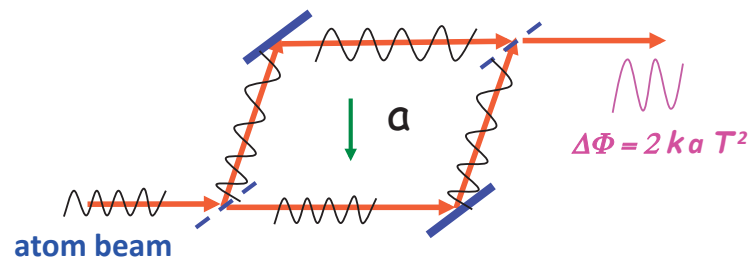
Sagnac effect: $\Delta\Phi = 8\pi(\mathbf{A} \cdot \boldsymbol{\Omega})/\lambda v$



Laboratory AI gyroscopes have demonstrated a sensitivity of $6 \times 10^{-10} \text{ rad s}^{-1} \text{ Hz}^{-1/2}$. [T. L. Gustavson et al., Class. Quantum Grav. **17**, 2385 (2000)]

Acceleration/gravity sensing

Phase shift due to acceleration: $\Delta\Phi = 2k a T^2$



Laboratory AI accelerometers have measured g with a resolution of $2 \times 10^{-8}g$ in 1 s and $3 \times 10^{-9}g$ overall precision. [A. Peters et al., Metrologia **38**, 25 (2001)]

There are also many related atom interferometer devices with BEC and cold atoms in waveguides ...



Inertial Phase Shifts in Atom Interferometers

For atom interferometer
accelerometer

$$\Delta\Phi = 2k a T^2$$

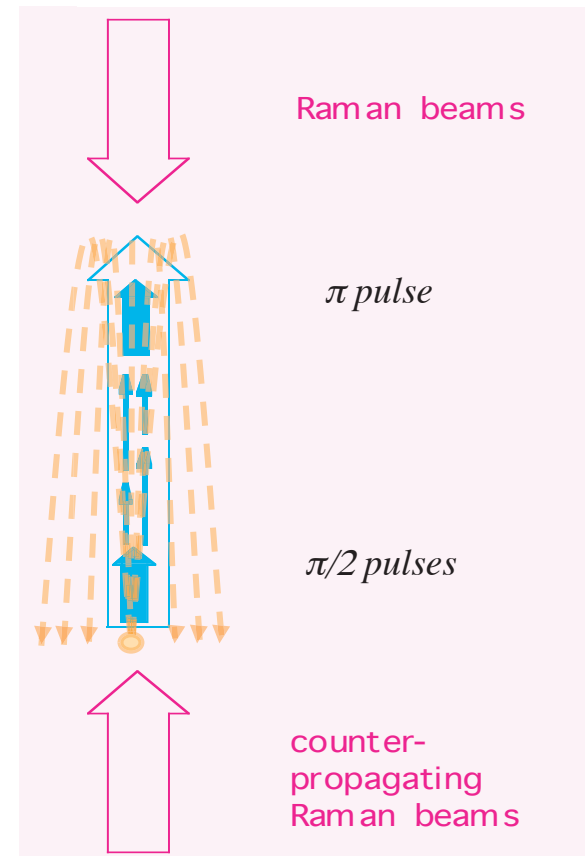
- Independent of atom initial velocity.
- The laser wavenumber k is the only reference parameter.
- Sensitivity increases with T^2 .

With over 10^6 atoms, the shot-noise limited SNR ~ 1000 .

Per shot sensitivity = $2 \times 10^{-10}/T^2$ m/s².

Great enhancement of the sensitivity can be gained in the microgravity environment in space!

Atomic fountain on ground



$10^{-13}g$ Hz^{-1/2} possible in microgravity with ~ 10 s interrogation time.



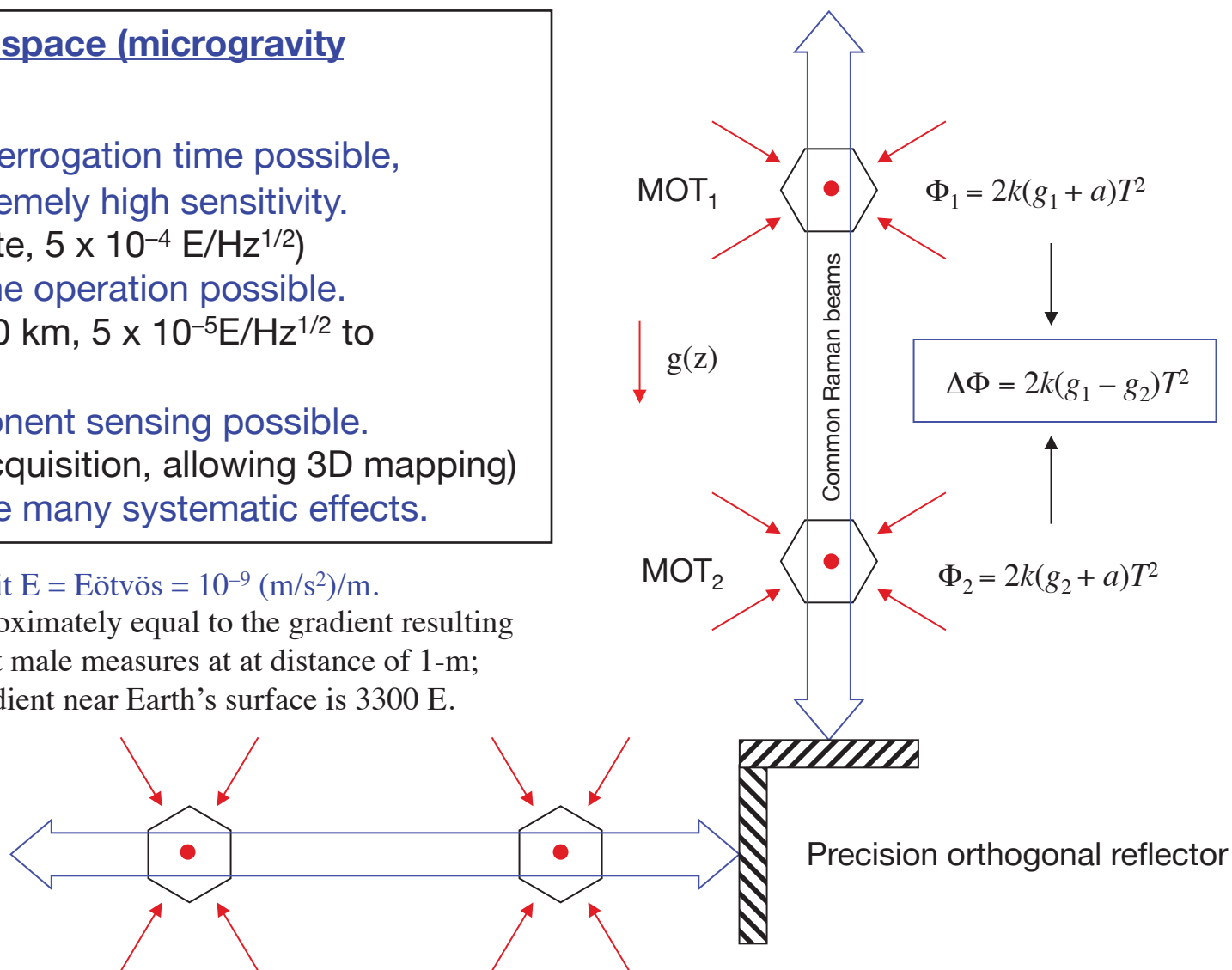
Space-Based Atomic Gravity Gradiometer

Advantages in space (microgravity environment):

- Very long interrogation time possible, resulting in extremely high sensitivity.
(single satellite, $5 \times 10^{-4} \text{ E/Hz}^{1/2}$)
- Long baseline operation possible.
(100 m to 200 km, $5 \times 10^{-5} \text{ E/Hz}^{1/2}$ to $3 \times 10^{-8} \text{ E/Hz}^{1/2}$)
- Multi-component sensing possible.
(full tensor acquisition, allowing 3D mapping)
- Helps reduce many systematic effects.

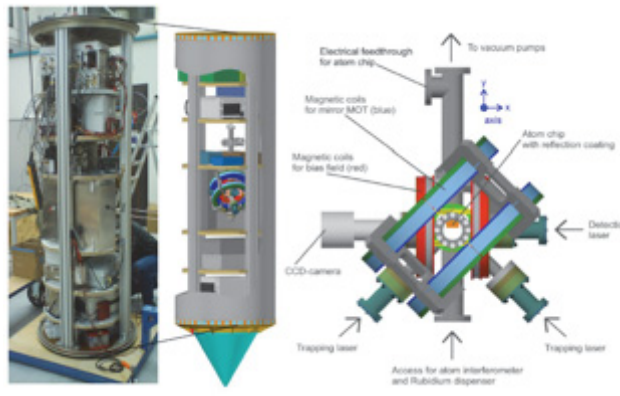
Gravity gradient unit $E = \text{Eötvös} = 10^{-9} (\text{m/s}^2)/\text{m}$.

1 E gradient is approximately equal to the gradient resulting from one adult male measures at distance of 1-m;
average gravity gradient near Earth's surface is 3300 E.





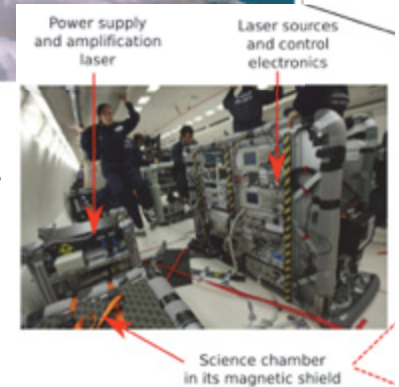
AI Technology Development for Space



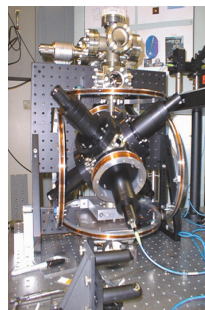
Drop tower Experiments with cold atoms and BEC, Quantus collaboration, DLR



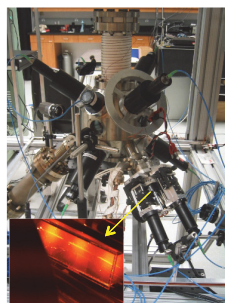
Atom interferometer in 0g flight, I.C.E. collaboration, France



JPL atom interferometer gravity gradiometer development



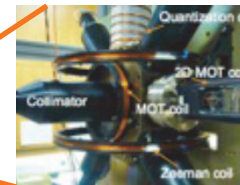
First tabletop experiment



2nd generation laboratory system



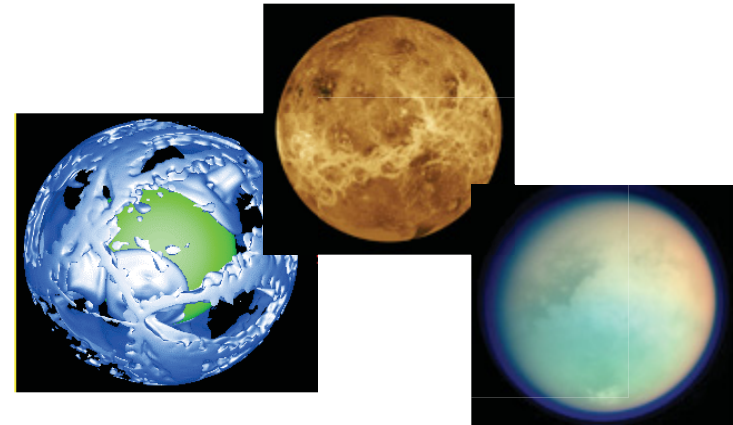
Transportable unit





Advanced Gravity Missions for Earth Science

- Cold atoms as truly drag-free test masses
- Gravity gradiometer (better resolution)
- Simpler mission architecture (single spacecraft)
- More flexible orbits and satellite constellation (more comprehensive data for data analyses)



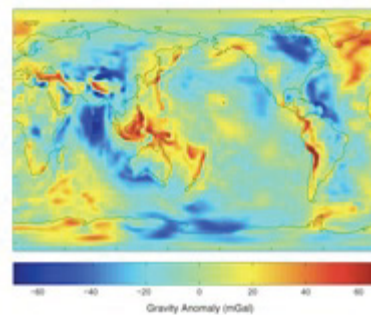
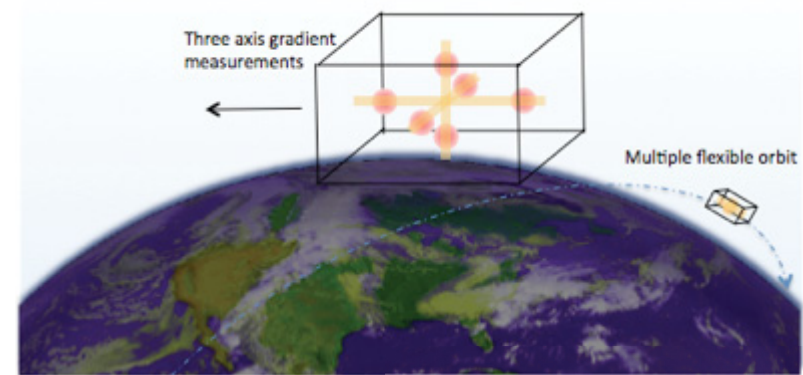
Geodesy

Earth and Planetary Interiors

- Lithospheric thickness, composition
- Lateral mantle density heterogeneity
- Deep interior studies
- Translational oscillation between core/mantle

Earth and Planetary Climate Effects

- Oceanic circulation
- Tectonic and glacial movements
- Tidal variations
- Surface and ground water storage
- Polar ice sheets
- Earthquake monitoring

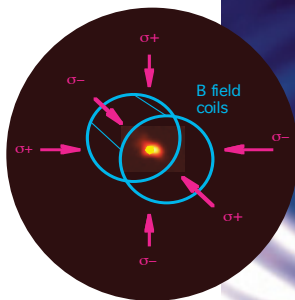




Fundamental Physics Experiments in Space

Precision inertial measurements for advancement of science

- Test of Einstein's Equivalence Principle with differential acceleration measurements of two atomic species
- Frame-dragging test of the General Relativity Theory with two pairs of atom gyroscopes and a precision star tracker
- Large scale gravity investigation
- Tests of inverse square law
- Gravitational wave detection



Gravitational wave detection

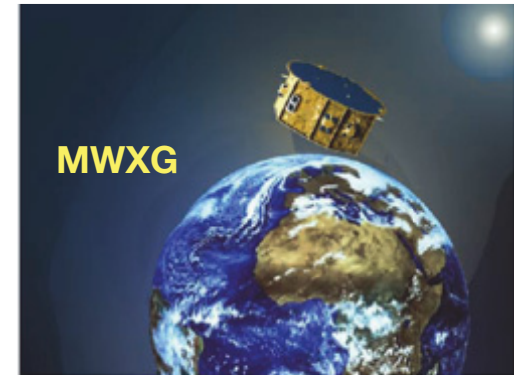
Inverse square law at short distances

Spin-gravity coupling



QuITE

Quantum Interferometer Test of Equivalence Principle



MWXG

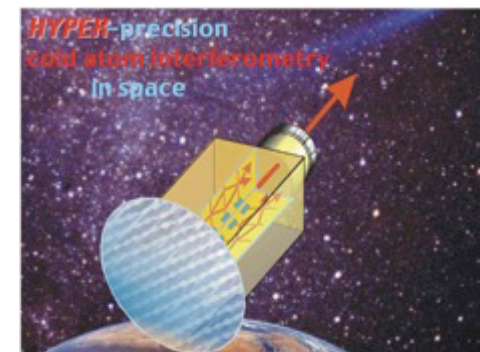
The MWXG spacecraft overall configuration

Matter Wave Explorer of Gravity



SAGAS

Quantum physics exploring gravity in the outer solar system

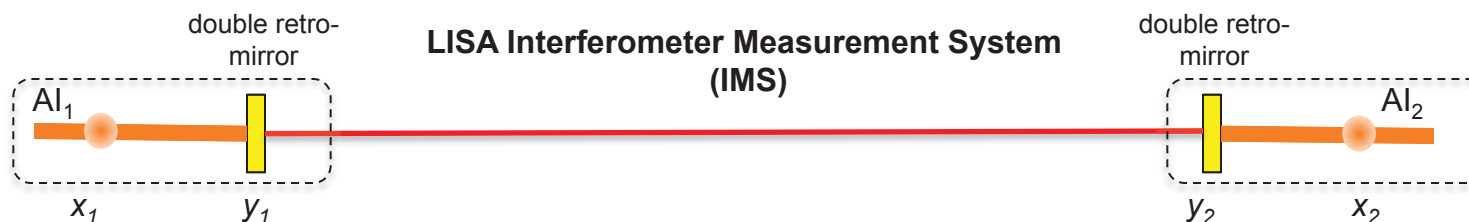
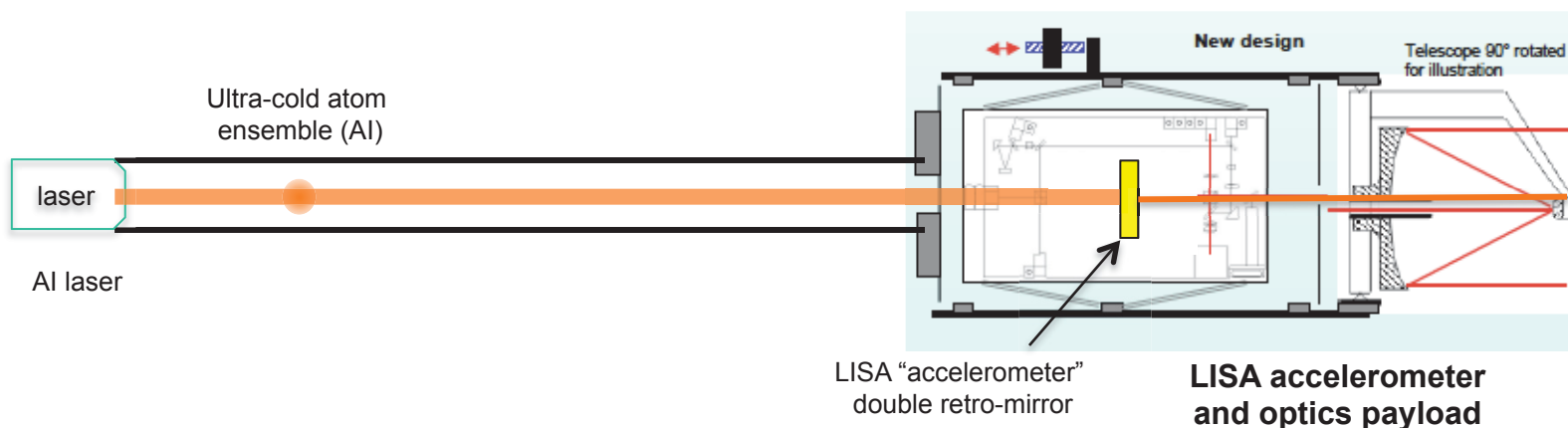


HYPER-precision cold atom interferometry in space

Precision measurements of Lense-Thirring effect



LISA Drag-Free Atomic Reference DRS Concept



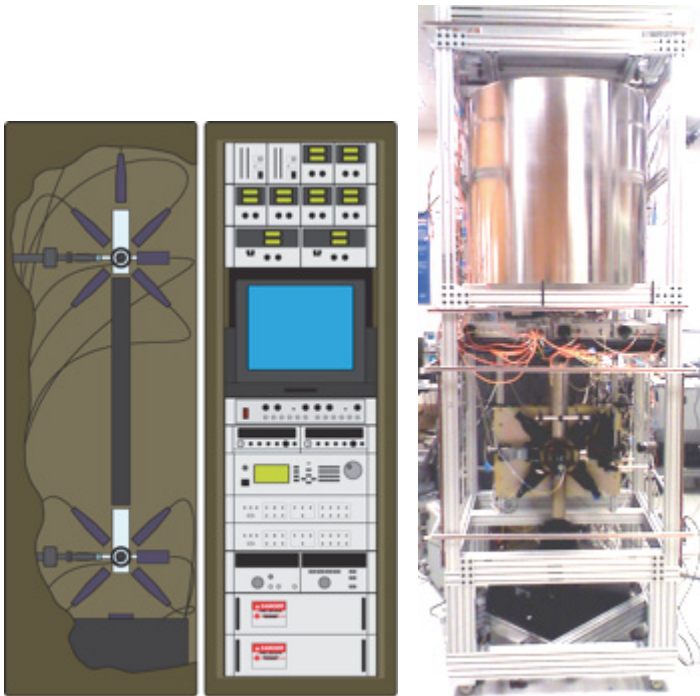
$$\Delta X = x_2(t) - x_1(t) = \underbrace{[x_2(t) - y_2(t)]}_{\text{Measured by AI}_1} + \underbrace{[y_2(t) - y_1(t)]}_{\text{Measured by IMS}} + \underbrace{[y_1(t) - x_1(t)]}_{\text{Measured by AI}_2}$$

Displacement jitters of the mirrors completely cancel, thereby reducing the spacecraft "accelerometer" drag-free requirements.



Precision Measurements with Cold Atoms at JPL

JPL's focus is toward space applications using cold atoms as freefall test masses ...



Ground-based transportable instrument is an interim technology development step

Atom interferometer specific

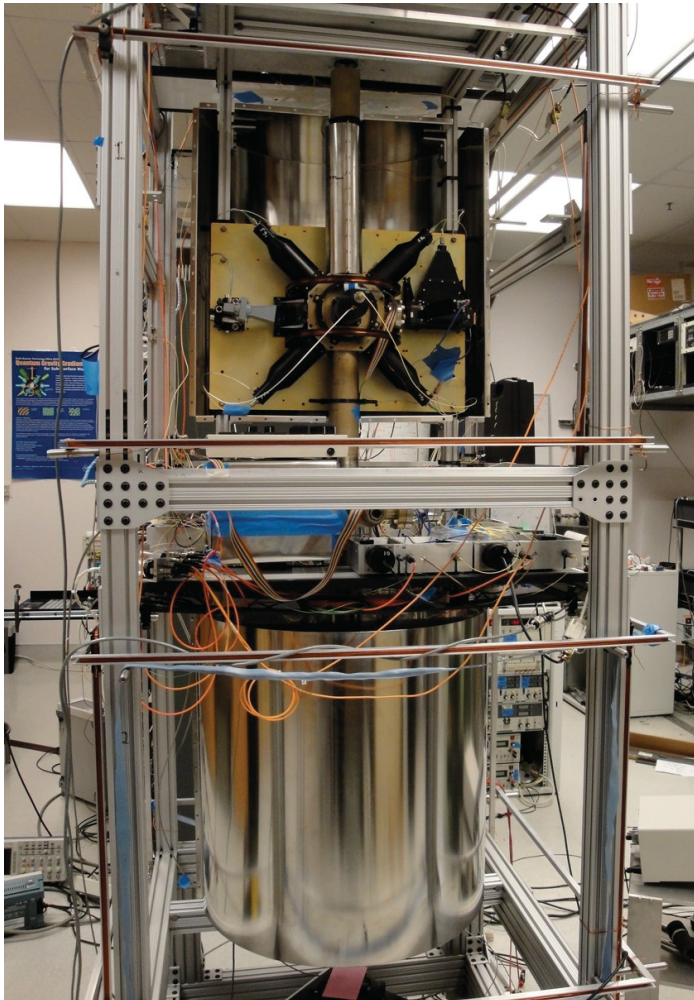
- Compact high-flux cold atom source
- Sealed ultra-vacuum system techniques
- Direct detection configuration
- 0-g compatible compact physics package design
- Dynamic range enhancement
- Robust and flexible optics system architecture
- Atom interferometer as atomic drag-free reference

General relevant competence

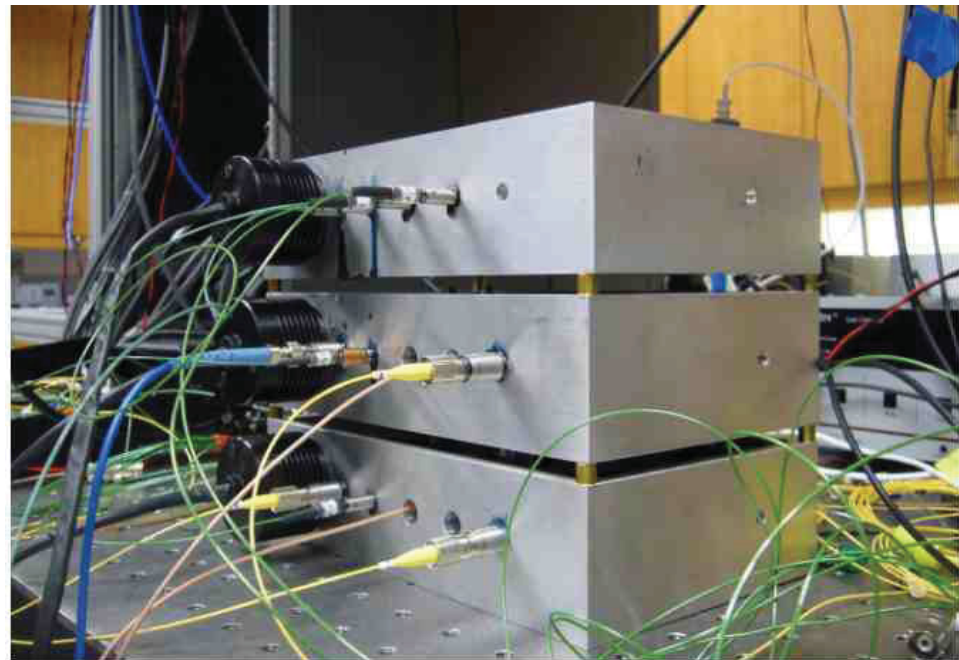
- Space cold atom system development heritage
- Related atomic clock development experience and competence
- Precision optical instrument development capability
- Core competence in Earth and planetary gravity measurements and instruments.



Transportable Gravity Gradiometer at JPL

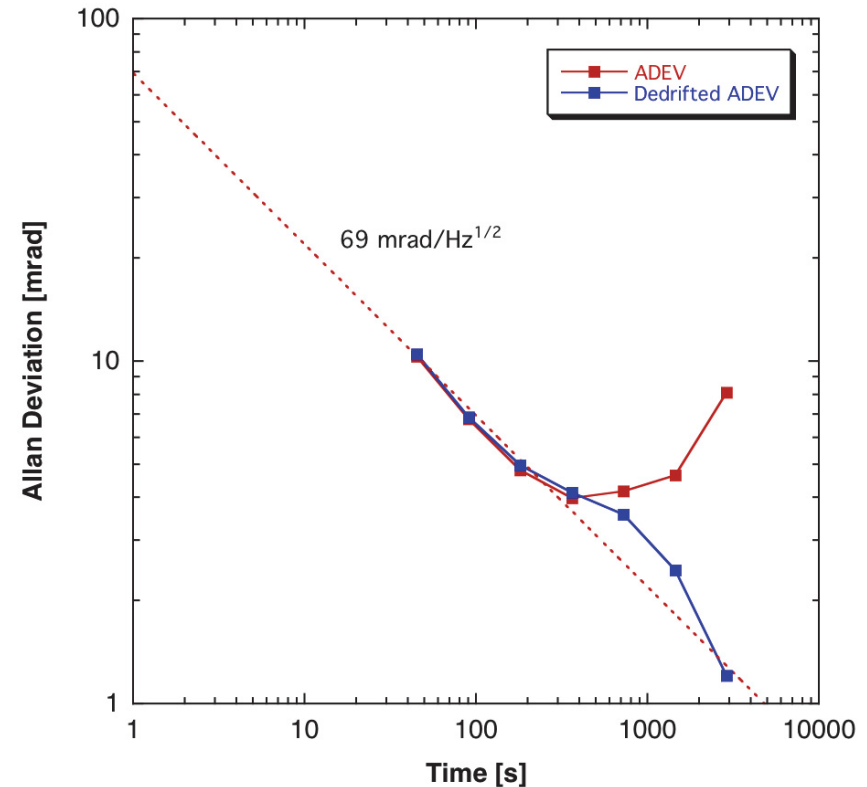
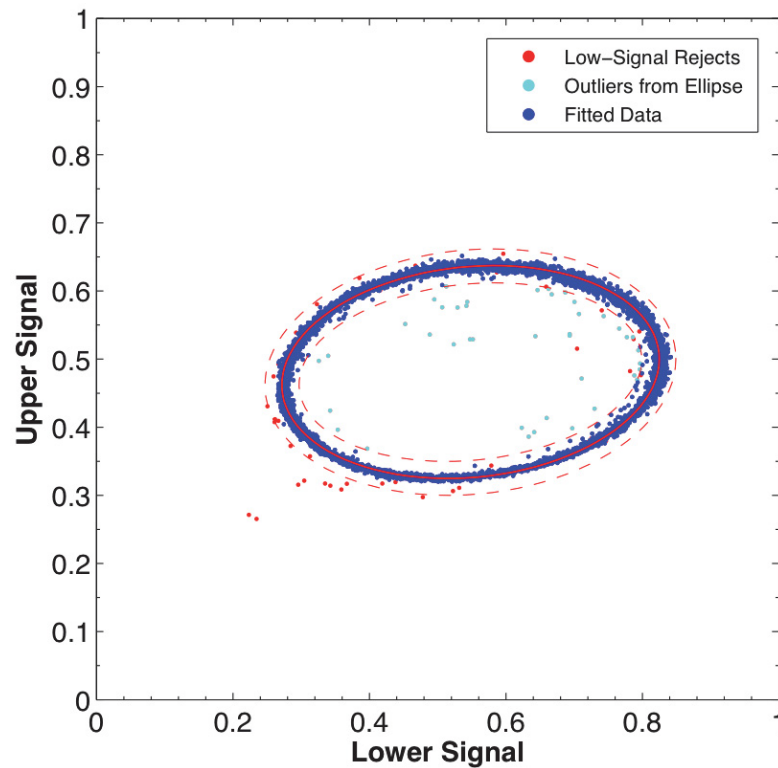


Left: Dual atom interferometer-based **gravity gradiometer** in the laboratory. The magnetic shields around the upper sensor have been partially removed to reveal the vacuum enclosure and laser optics.
Below: Stacked array of laser amplifier modules from the **laser and optics system**.





Gravity Gradiometer Data and Sensitivity Analysis

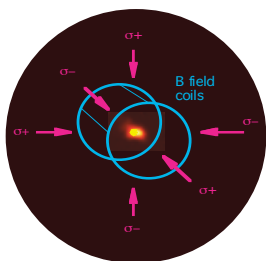


Parametric plot of atom interferometer signals in the gravity gradiometer (*left*) and Allan deviations for the relative phase *with* and *without* removing a linear drift (*right*). $N = 5400$.



Conclusion: Cold Atomic Sensors in Space

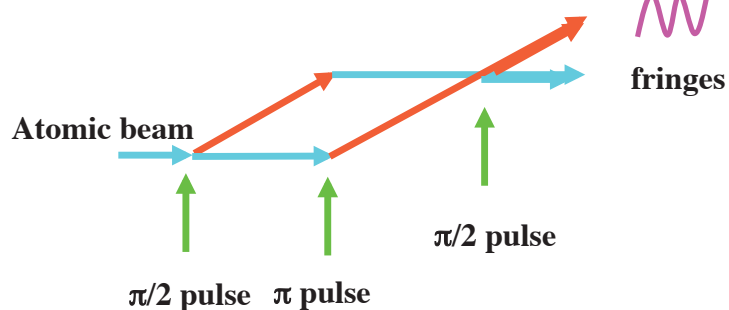
Freefall test mass



Laser-cooled Cs
atom cloud at μK

+

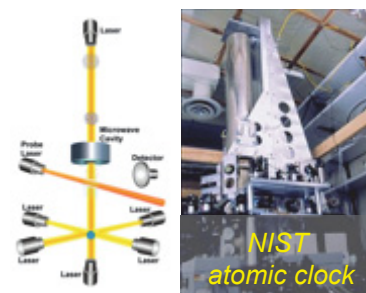
Displacement Detection



atom-wave interferometer
(laser-based atom optics)

+

Atomic system stability



Atoms are stable clocks

- **Use identical freefall atomic particles as ideal test masses**
 - *Identical atomic particles are collected, cooled, and released free fall in vacuum with no external perturbation other than gravity/inertial forces.*
 - *Laser-cooling and trapping are used to manipulate the cold atomic test masses.*
 - *No cryogenics and no mechanical moving parts.*
- **Matter-wave interference for displacement measurements**
 - *Displacement measurements through quantum interference, $\text{pm}/\text{Hz}^{1/2}$ when in space.*
- **Intrinsic high stability of atomic system**
 - *Use the very same atoms and measurement schemes as those for the most precise atomic clocks, allowing high measurement stabilities.*
- **Enable orders of magnitude sensitivity enhancement when in space**
 - *Microgravity environment offers long interrogation times with atoms, orders of magnitude higher sensitivity compared terrestrial measurements.*



Thank You!

POC for further information:

Dr. Nan Yu

email: nan.yu@jpl.nasa.gov

phone: (818) 354-4093